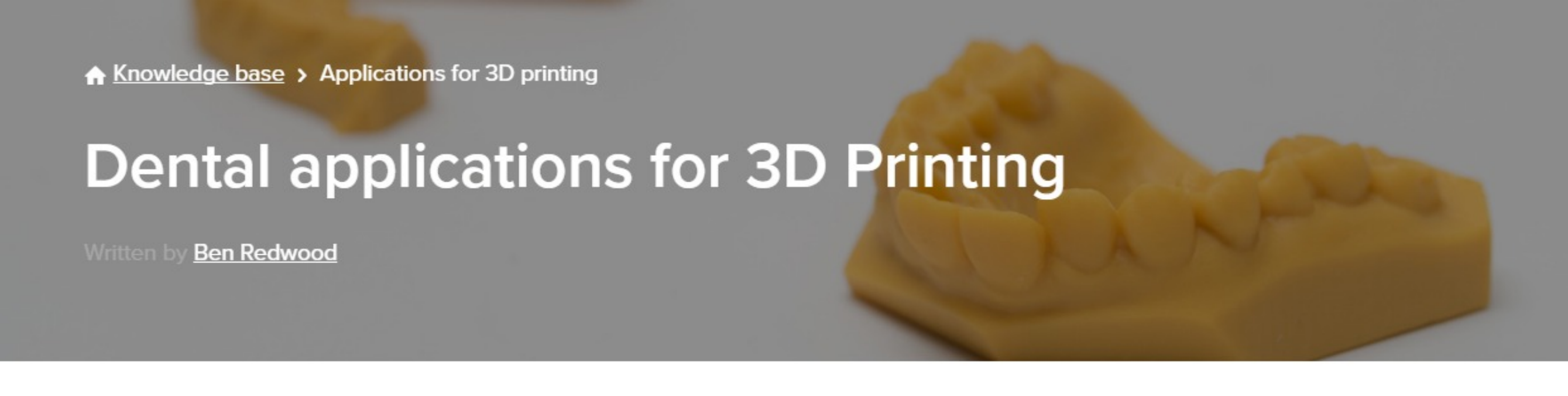


Dental applications for 3D Printing

Written by Ben Redwood

This article will discuss the requirements within the dental industry that make AM an ideally suited technology for many applications.

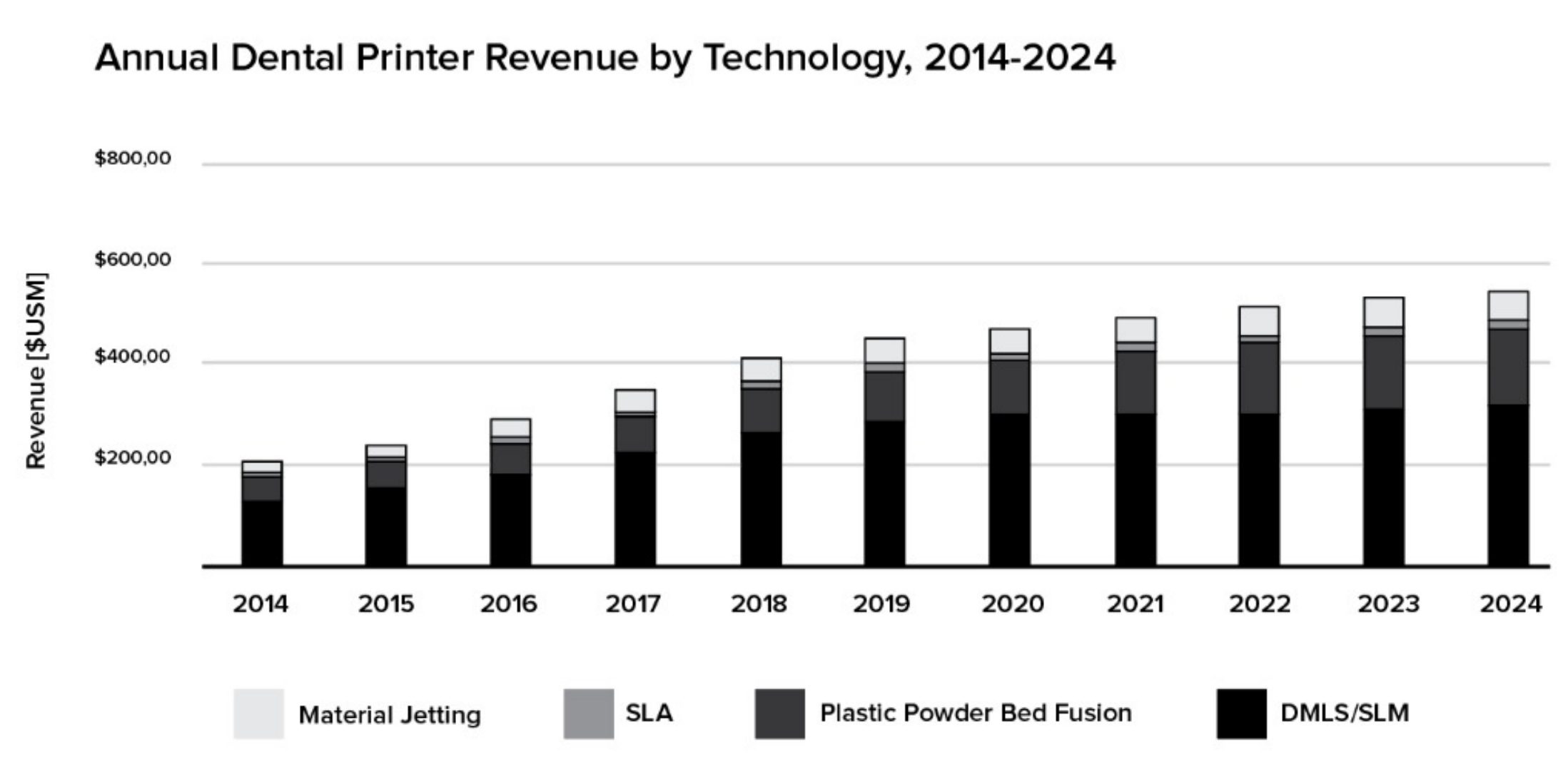
Table of contents

Introduction

Modern dentistry relies heavily on the ability to produce small, complex components that fit perfectly inside the mouth. Every set of teeth is unique, meaning that every dental appliance has to be custom-made. Because of theses constraints, additive manufacturing (AM) is now employed in large range of dental applications. The dental and medical industry now account for over 13% of all AM revenue annually. Align Technologies manufactures 17 millions Invisalign orthodontic aligners annually, and each one is produced by thermoforming sheet material over a unique pattern made by AM. Meanwhile, according to EOS, more than 5 million metal copings (used to produce crowns and bridges) are being produced on its AM equipment every year.

AM's high level of detail, rapid build time and design freedom, coupled with the growing range of biocompatible dental materials means the technology is no longer a complicated, expensive novelty but commonplace in many orthodontic practices around the world.

This article will present why AM has been embraced by the dental community. It will discuss dental industry requirements and common data generation techniques that confirm why AM is ideally suited to so many dental applications. Limitations of the technology will also be discussed.



Estimated annual dental printer revenue by technology, 2014 - 2024 (*Source: SmarTech Markets Publishing, 3D Printing in Dentistry 2015*)

Medical industry requirements

Customisation

As with the medical industry, the most critical factor in the design and production of orthodontic components is the need to tailor them to a patient's specific anatomy. AM is perfectly suited for highly customised, one-off production of parts.

Materials

One of the limiting factors in the industry-wide adoption of AM for dental applications has been the lack of appropriate materials. Until recently, dentists were only using AM for the production of models. Advances in industry has seen a large increase the availability of biocompatible AM materials (in particular dental resins).

Lead time

Traditionally, many of the components used in orthodontics were produced based on casting or impressions made by the dentist. These impressions were sent out of house to be utilized as a reference when fabricating a crown, dentures, or other types of restorations. This resulted in a long delay between the initial dental consultation and the final implant procedure with some ceramic crowns taking over a week to produce. The rapid build time of AM means that from a 3D scan, a ready to use component can be produced in a matter of hours, with some instances allowing the consultation, scan, print and implant procedures to occur on the same day.

Complexity and accuracy

Traditional processes for fabricating dental parts rely heavily on the skill of a craftsman and mean that errors or variations are not uncommon while the multistage nature of investment casting (used regularly in the production of dental implants) means that small defects are often compounded. The need to insert the orthodontic components into a harsh environment that isn't easily accessible while achieving a perfect fit means that highly complex, accurate geometries are needed. Even small variations in accuracy can cause discomfort or have a negative impact on the outcome of a patient. AM is able to produce complex, highly accurate parts in a single step that perfectly match digital scan data.

Data generation

One of the most important steps in the production of dental parts via AM is the generation of an STL file from scan data. Being able to produce patient specific components directly from scan data is one of the main strengths of AM. There are a number of techniques used in the orthodontic industry to obtain scan data that can then be converted to an STL file for printing.

Data collect via scans of patients can be used to produce anatomical models with AM. Here an intraoral scan produces a 3D model of a patients mouth (image courtesy of AVINENT).

CBCT - Cone beam computed tomography (CBCT) is a popular method of scanning that is able to produce 3D digital models from scan data. A 200 degree rotation around the patient's mouth acquires a volumetric data set. Scanning software then uses this data to producing a digital volume composed of three-dimensional voxels that can then be manipulated and visualized with specialized software. CBCT offers excellent feedback for treatment planning and diagnosis in implant dentistry, providing information on the bone, bone density, soft tissue and nerves. Using the generated 3D file allows the dentist is to insert digital implants and run a series of tests to determine the optimal location and orientation.

Intraoral scans - Intraoral scanning is one of the fastest growing areas in dentistry. The compact, hand held scanners are moved back and forth around a patient's teeth and produce a full colour scan model in real time. Most intraoral scanners produce an STL file and software then allows the model to easily be manipulated. There are two types of intraoral scanners available:

- Systems that use a blue LED (light-emitting diode) are optical scanners that depend upon a reflective surface and require a contrasting medium or powder to acquire a representation of the tooth morphology.
- Systems that use laser technology to scan and measure distances from the tooth surface to acquire the image. They do not require powder.

Intraoral scanners are very accurate and very quick to use however some training is generally required to produce a high quality scan.

Scanned impressions - Polyether or polyvinyl siloxane (PVS) molding is a traditional dental technique used to create impressions of patients teeth. These molds are then cast using an impression compound like plaster of Paris. The casting is then 3D scanned using desktop scanner system to produce an accurate digital file. Scanned impressions are a common method for producing 3D files of patients teeth as they use traditional techniques that dentists are familiar with in conjunction with with modern technologies that improve workflow and accuracy.

Combined methods - For highly accurate 3D models, scan data from intraoral or scanned impressions is combined with CTCT data. The intraoral or scanned impression STL file can be overlaid onto the digital imaging and communications in medicine (DICOM) image from a CBCT scan providing a comprehensive STL file be imported into guided surgery software.

Common applications

Crowns and bridges

Crowns and bridges printed directly via AM (image courtesy of NextDent)

The methods for producing crowns and bridges can vary however typically they are made via the investment casting process or CNC milled from a solid block of porcelain. Both of these methods present limitations; investment casting requires a large number of stages increasing lead time while small, intricate and brittle CNC machined parts must be designed to withstand the high forces produced by the cutting tool. AM is now utilized at various production stages in the fabrication of dental crowns and bridges. Each of these are summarised below:

Investment Casting patterns - The most popular use of AM when producing crowns and bridges is the printing of castable models to be used as an investment pattern during the investment casting process. From 3D scan data a model of the crown or bridge is produced. This model is then printed in a castable resin that is able to be burnout during the casting process. The nature of AM allows for a large number of unique, accurate bridges and crowns to be produced in a single build with few limitations on geometry and complexity. This reduces lead overall lead times and allows AM be very cost competitive when compared to wax models made from cast patient impressions.

Metal printing - Traditional metal crowns and bridges are made from a range of materials including gold, platinum, palladium, silver, copper and tin. The metal parts are used either as the coping with a porcelain layer applied to the outside or are polished and used directly. Metal AM has become a popular option in the dental industry with the direct metal printing of crowns and bridges now commonplace. Being able to produce parts directly from metal reduces the lead time of the investment casting process while the ability to produce hundreds of parts in a single print further accelerates the production process.

A large number of metal crown and bridge copings printed in a single prints (image courtesy of Renishaw)

Direct printing - With the development of new materials, AM is now able to print the crowns and bridge of up to 3 teeth directly. Materials like NextDent C&B offer excellent abrasion resistance and strength and are compatible with traditional dental cements. As the speed of AM increases, technologies offer the ability to perform an intraoral scan and deliver a crown or bridge to a patient in a single appointment.

Technology	Best suited for
SLA	SLA can produce crowns and bridges from castable resin as well as print them directly from tough, biocompatible materials.
Material jetting	Material jetting can produce highly accurate patterns for the investment casting process. Drop on demand (DOD) technology is able to produce accurate, detailed wax models.
DMLS/SLM	AM metal printing is able to produce batches of 500 accurate metal copings in a single print from a range of materials including gold and cobalt-chrome.

Orthodontic models

Orthodontic models were one of the first applications of AM in dentistry. Using scan data from a patient a low cost model can rapidly be created giving a dentist an insight into the anatomy of a patient. Orthodontic models allow dentists to examine tooth location and orientation, test fit and clearance of orthodontic appliances, crowns, bridge and other dental components and also practice procedures.

Highly accurate dental models produced via AM give dentists a better understanding of a patients teeth.

While historically dental models were cast from impressions, 3D scan data allows models to be directly printed. Models can be printed in a range of materials, can include removable dies and are printed at a very high accuracy.

Technology	Best suited for
SLA	SLA offers excellent dimensional stability of model designs and produces a precise, smooth and pore-free model surface.
Material jetting	High detail models with some printers offering multi-material, full colour prints.

Surgical/dental guides

A dental tool guide. Scanning the patients teeth then 3D printing the design allows for the tool to be perfectly located (image courtesy of Formlabs).

Traditionally, surgery was either done by hand, or surgical guides were fabricated on solid stone (gypsum) models or laboratory-fabricated dentures, and holes were pre-drilled to guide the dental surgeon's tool. With AM, highly accurate, custom surgical guides that precisely match the patient's anatomy are able to be produced. From a digital file of a patient's mouth, a surgical guide can be designed. Holes are included in the design to direct the surgeon's tool piece to the exact location it is required. Once the design is complete it is sent to the printer. After the print is finished the holes are fitted with metal sleeves and used in conjunction with drill-guide sleeves that control and guide the drill to the correct procedure location and depth. Estimates put the average cost saving when producing dental guides with AM, when compared to traditional techniques, at 50 percent to 85 percent.

Technology	Best suited for
SLA	The high accuracy of SLA parts make them ideally suited for surgical guides. A large range of biocompatible, transparent materials are available in varying stiffnesses.
Material jetting	Surgical guides made using material jetting use materials that are approved for using short-term mucosal membrane contact of up to 24 hours. The guides are highly accurate and transparent.

Orthodontic appliances and indirect bonding trays

A trandparent functional dental appliance used in conjunction with a dental model - both printed via AM (image courtesy of Stratasys).

One of the biggest problems with treatment appliances is that if they cause discomfort patients are generally less likely to use them. The high level of accuracy and customisation offered by AM means that appliances are more likely to fit better resulting in patients being less reluctant to use them. Orthodontic appliances and indirect bonding trays are now regularly produced via AM based upon scans of patients teeth. There are 2 common methods for fabricating appliances and trays:

Thermoforming - Thermoforming offers a quick, low cost method for producing orthodontic appliances and indirect bonding trays. A solid model (or mold) of a patient's teeth is printed using AM from scan data. The mold is the placed in a dental specific thermoforming machine that used a heated plastic sheet and a vacuum to form a solid plastic shape over the mold. The plastic part is then trimmed to size. The high accuracy, strength and smooth surface of molds produced via AM make it an ideal solution for thermoforming when compared to the brittle casting materials that are traditionally used.

Direct printing - AM is also able to produce orthodontic appliances and indirect bonding trays directly eliminating the need for molds or trimming of the thermoformed parts. From scan data, the dental components can easily be produced. AM offers a range of transparent, biocompatible materials that are to be used specifically for dental applications and indirect bonding trays.

Technology	Best suited for
SLA	SLA is used for both the production of thermoforming molds as well as direct printing of the . The additive nature of AM means that several orthodontic appliances can be printed in a single run.
Material jetting	Material jetting is able to produce transparent orthodontic appliances of varying stiffnesses as well a very accurate molds for thermoforming.

Denture bases and frames

The production of entire dentures made with AM is still uncommon. AM technologies are either combined or used in conjunction with traditional dental techniques. Denture bases, however, are regularly made via AM. Denture bases require materials that do not experience shrinkage, are lightweight and stiff and also biocompatible.

A complex and custom metal denture frames printed using metal AM. The image on the left shows the part with the support structure still attached (image courtesy of EOS).

AM metal printing is also now used in the production of denture frames. Cobalt chrome is commonly used. Because of metals superior strength when compared to plastic the bases can be thinner making the denture more comfortable. Metal denture bases are made with the clasp built into the frame resulting in improved fit and strength of the clasp. The design freedom of AM also means the metal sections can be highly complex and topographically optimized.

For both plastic and metal denture bases fabricated using AM, the denture teeth are produced and fitted using traditional orthodontic techniques.

Technology	Best suited for
SLA	SLA is ideal for producing high detail, plastic, biocompatible denture bases printed in colors that match the gums.
DMLS/SLM	Metal denture frames are now regularly produced by AM. Metal AM parts can be made from a number of common dental metals and can easily produce very complex geometries.

Custom impression trays

Complex and custom metal denture frames produced using AM (image courtesy of Roland).

Impression trays are used for taking impressions of patients teeth. These impressions are then used to produce cast models. Impression trays are typically generic in design with several increments of size available. While basic trays are sufficient most of the time there are customers who require a custom tray, requiring modifications to be made to the generic design to improve patient comfort and achieve the best possible impression. AM allows for the rapid production of low cost, individualised trays. The smooth and accurate surfaces of AM parts form the basis for an excellent fit and retention holes can easily be included in a design removing the need for any drilling.

Technology	Best suited for
SLA	Custom trays that require a very smooth surface. Trays can be produced very quickly from a range of stiff and flexible materials.

Limitations

Some of limitations of AM when applied to the dental industry include:

- All the AM technologies described in this article require support material to successfully print parts. The support material must then be removed once the print is complete. While material jetting offers support that is dissolvable in water both SLA and DMLS/SLM require significant post processing after printing to achieve a smooth surface on the areas where support was located. This increases the lead time and cost of the AM process.
- The cost of purchasing the equipment required to produce castings from impressions is far lower than the cost of a new SLA or material jetting printer (which range from $4000 up to $100,000). The materials used for AM are also expensive.
- While AM is now firmly established in the dental industry as a disruptive technology, a critical part of the success of any part produced with AM is the users understanding of design for additive manufacturing (DFAM). DFAM requires users to understand the limitations of the technology and how to optimize a design to achieve the highest quality part. Orientation, layer height, support locations and materials all play an important role in whether a part will print successfully to a high degree of accuracy.

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